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Measuring the Consumer Welfare Effects of Carbon Penalties: Theory and Applications to Household Energy Demand

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Abstract

This study implements a money metric approximation to the Hicksian equivalent variation (HEV) based on observable demand functions. This money metric welfare measure is a less restrictive approximation to the HEV than the Marshallian consumer surplus (MCS) in situations where MCS is misleading, e. g., when more than one price changes at the same time. This study also implements a generalized logit demand system that conforms better to the theory of consumer behavior than standard flexible functional forms, e. g., translog, the "almost ideal demand system" (AIDS), generalized Leontief and minflex Laurent models.

The generalized logit model was estimated using New York state level and company level data on residential consumption of electricity, natural gas and fuel oil, including a composite good to complete the demand system. The estimated model satisfied the theoretical conditions of a well-behaved demand system for every data point in the sample and for a range of hypothetical households which are distinctly different from the sample. The demand model and money metric were combined to measure the consumer welfare effects of carbon penalties on electricity and fuels. While the application is specific, the generalized logit model of demand and the money metric measure of welfare change can encompass a wider range of applications than conventional methods of analysis.

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1. Introduction and Summary

Increased attention is being devoted to the analysis of environmental externalities generated by economic activities. For example, the emissions of sulfur dioxide, nitrogen oxides and carbon from the generation of electricity are central issues in the discussion of externalities in the New York State bidding process.[1] Furthermore, there is increasing interest nationally and internationally in policy proposals to reduce carbon emissions. The taxation of carbon emissions is one way for society to internalize environmental externalities relative to global warming by imposing monetary penalties per unit of carbon emitted from all fuels. This contrasts with the bidding process because the latter adds cost to electricity generation only. However, in both cases electric utilities are in a position to pass on these charges to their customers through increased rates. Consequently, there are inevitable effects on the welfare of consumers, and the monetary measurement of these welfare effects is the primary focus of this paper.

The measures of welfare effects presented in this paper are based on a money metric measure of welfare change (Dumagan, 1989), which is presented in section 2 as a superior alternative to the traditional Marshallian consumer's surplus (MCS). The rationale for this money metric is that it can be used to evaluate the effects of multiple price changes from, for example, a carbon tax on all fuels. The money metric welfare calculations are based on estimates of a complete residential energy demand system using a generalized logit model (Dumagan & Mount, 1991). The theoretical properties of this

[1]This bidding process entails adding an environmental penalty per unit of energy (kilowatt-hour) to the marginal cost of this new source. In principle; cleaner generating plants are subject to lower penalties to reflect lower social costs of power production.

logit model vis-a-vis other demand systems such as the translog and AIDS models are briefly outlined in section 3. A dynamic version of this generalized logit model was estimated using residential sector data for the state of New York from 1960 to 1987 for electricity, natural gas, fuel oil and a composite "other" commodity to complete the demand system. The estimation results are summarized in section 4.

The flexibility of the generalized logit model is illustrated by using the parameter estimates from the statewide residential energy demand system to calibrate energy demand elasticities for different households. These are specified to represent low income, middle income and high income households, where in each income category households are further differentiated by the source of energy for heating (electricity, natural gas or oil). Welfare effects are then calculated for each of the nine representative households from the price increases due to (a) the imposition of a tax per ton of carbon applied to the different emission rates of carbon for electricity, natural gas and oil, and (b) a tax applied to electricity only (i.e. similar to the implications of incorporating environmental costs into the bidding process). The specified household characteristics, calibrated energy demand elasticities and welfare effects for each household are presented in sections 5 and 6.

The main results are summarized in Table 10 for the two different policies. Their importance is not so much in the numerical values but in demonstrating that (a) the generalized logit model can be calibrated to represent different types of households without violating the desirable economic properties of the model, (b) the demand elasticities for different households change consistently with economic logic, and (c) the money metric measure of welfare change can be used to evaluate a wide variety of environmental policies.

2. The Money Metric Measure of Welfare Change

In theory, a consumer has a utility function representing the consumer's level of welfare expressed as a function of the consumption levels of different goods. Also, the consumer faces a budget constraint which constrains the purchases of each good given their prices and the consumer's income. By maximizing the utility function subject to this budget constraint, the consumer's purchases of goods can be summarized by his demand functions, which give the quantities demanded of each good at different prices, given the prices of the other goods and income. If the demand functions are substituted into the original utility function, utility becomes a function of prices and income. The latter is generally known as the consumer's "indirect" utility function which describes the consumer's level of welfare as a non–increasing function of prices, non–decreasing function of income, and homogeneous of degree zero in prices and income. In general, with everything else remaining the same, consumer welfare decreases (increases) when prices rise (fall); increases (decreases) when income rises (falls); and remains the same when all prices and income change by equal proportions in the same direction, since in the latter case real purchasing power must remain the same. Most measures of welfare changes attempt to give a monetary value corresponding to an amount of income that is lost or gained.

If the form of the utility function is known, the measurement of welfare change becomes a simple matter indeed for then it can be calculated from the change in the value of the indirect utility function due to the change in the original levels of prices and income. In practice, welfare change measurement becomes problematic when it is based on estimated demand functions which are not explicitly derived from a given utility function, i.e., when the underlying utility function is unknown or arbitrary. However, it remains possible in the latter case to measure changes in consumer welfare given a change in prices and/or income. For instance, the traditional Marshallian consumer's surplus (MCS) as well as the money metric alternative are based solely on estimated (Marshallian) demand functions, and the issue between these two competing measures revolves around the implied restrictions on the underlying utility function that will make one or the other an acceptable measure of welfare change.

The MCS is an acceptable measure of welfare in the special cases where (a) there is a change in only one price or (b), if there is a change in more than one price, the goods with the changing prices have identical income elasticities of demand, though not necessarily all equal to one (Dumagan, 1989). As a generalization of case (b), if all prices are changing, then the MCS is an acceptable measure of welfare change if and only if all income elasticities of demand are unitary, i.e., the underlying utility function is homothetic. If there is a change in more than one price at the same time, the MCS is not an acceptable measure of welfare change when the income elasticities (of the goods with changing prices) are not all equal. In this case, the MCS can be shown to be dependent on the path of integration, i.e., on the evaluation of the MCS integral with respect to the pattern of price changes. The result is that there are multiple values of the MCS given the same pattern of price changes. The implication for practical applications is that the MCS is a misleading or ambiguous measure of welfare change in the more general case of multiple price changes involving consumer goods with unequal income elasticities of demand. However, this is exactly the situation faced when evaluating a carbon tax or other policies that affect the prices of more than one fuel.

In the more general case of multiple price as well as income changes with no restrictions on income elasticities of demand, the correct measure of welfare change is the Hicksian equivalent variation (HEV). Unfortunately, the HEV is not in practice directly measurable because it is based on Hicksian demand functions which are not observable. However, the HEV can be approximated by the money metric proposed by McKenzie (1984). This money metric is theoretically derived from a Taylor series approximation to the change in an arbitrary indirect utility function assuming a simultaneous change in all prices and income. The derivation satisfies the necessary integrability conditions for the money metric to be a unique measure. The third–order money metric in particular has the same properties as the indirect utility function noted earlier, namely, non–increasing in prices, non–decreasing in income and homogeneous of degree zero in income and prices. Dumagan (1989) reformulated McKenzie's third–order money metric measure of welfare change into

$$\frac{MM_3}{I} = \frac{\Delta I}{I} - \sum_{i=1}^{n} w_i \frac{\Delta p_i}{p_i} - \sum_{i=1}^{n} w_i E_{iI} \frac{\Delta p_i}{p_i} \frac{\Delta I}{I}$$

$$+ \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} (w_i w_j E_{jI} - w_i E_{ij}) \frac{\Delta p_i}{p_i} \frac{\Delta p_j}{p_j}$$

$$+\frac{1}{6}\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\left(w_i\,p_j\,p_k\,\frac{\partial^2 x_j}{\partial I\,\partial p_k}+w_i\,w_j\,E_{ik}\,E_{jI}\right)\frac{\Delta p_i}{p_i}\,\frac{\Delta p_j}{p_j}\,\frac{\Delta p_k}{p_k}$$

$$-\frac{1}{6}\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}\left(\frac{p_i\,p_j\,p_k}{I}\,\frac{\partial^2 x_i}{\partial p_j\,\partial p_k}+I\,w_i\,w_j\,p_k\,\frac{\partial^2 x_k}{\partial I^2}\right)\frac{\Delta p_i}{p_i}\,\frac{\Delta p_j}{p_j}\,\frac{\Delta p_k}{p_k}$$

$$-\frac{1}{6}\sum_{i=1}^{n}\sum_{j=1}^{n}\sum_{k=1}^{n}(w_i\,w_j\,w_k\,E_{jI}\,E_{kI}-w_i\,w_k\,E_{ij}\,E_{kI})\,\frac{\Delta p_i}{p_i}\,\frac{\Delta p_j}{p_j}\,\frac{\Delta p_k}{p_k}$$

$$+\frac{1}{2}\sum_{i=1}^{n}\sum_{k=1}^{n}\left(I\,w_i\,p_k\,\frac{\partial^2 x_k}{\partial I^2}-p_i\,p_k\,\frac{\partial^2 x_i}{\partial p_k\,\partial I}\right)\frac{\Delta p_i}{p_i}\,\frac{\Delta p_k}{p_k}\,\frac{\Delta I}{I}$$

$$+\frac{1}{2}\sum_{i=1}^{n}\sum_{k=1}^{n}(w_i\,w_k\,E_{iI}\,E_{kI})\,\frac{\Delta p_i}{p_i}\,\frac{\Delta p_k}{p_k}\,\frac{\Delta I}{I}$$

$$-\frac{1}{2}\sum_{i=1}^{n}I\,p_i\,\frac{\partial^2 x_i}{\partial I^2}\,\frac{\Delta p_i}{p_i}\left(\frac{\Delta I}{I}\right)^2 \qquad [1]$$

where

$$I=\sum_{i=1}^{n}p_i\,x_i \quad ; \quad w_i=\frac{p_i\,x_i}{I} \quad ; \quad E_{ij}=\frac{\partial x_i}{\partial p_j}\,\frac{p_j}{x_i} \quad ; \quad E_{iI}=\frac{\partial x_i}{\partial I}\,\frac{I}{x_i}\;. \qquad [2]$$

In [1] to [2], x_i, $i = 1, \ldots, n$, are consumer goods with prices p_i; I is total expenditure (income); w_i is an expenditure share; E_{ij} is a price elasticity; and E_{iI} is an income elasticity. Thus, the money metric measures welfare change using the parameters of the estimated demand functions for consumer goods, in addition to the price and quantity data to determine the elasticities and expenditure shares defined by [2].

This money metric is practicable since it is based solely on observable Marshallian demand functions and embodies no theoretical restrictions other than those implied by utility maximization. These restrictions are (a) non–negativity and additivity of the budget shares to one, (b) negative Hicksian own-price effects and symmetric Hicksian cross-price effects, (c) zero–degree homogeneity in prices and income and (d) negative semi–definite Hicks–Slutsky substitution matrix. However, there is no particular restriction with respect to price and income elasticities other than those that follow from the above general restrictions.

3. A Generalized Logit Model of a Marshallian Demand System

The third–order money metric is applicable for measuring welfare changes for any empirical Marshallian demand system that embodies utility–maximizing behavior. While the demand system may not have been derived from an explicit utility function, there exists in principle a utility function that could have generated the demand system given that restrictions (a) to (d) above are satisfied. If so, the demand system is valid in combination with the money metric to measure welfare changes.

For the purposes of this paper, the parameters of a Marshallian demand system were estimated from a generalized logit specification of the budget shares in a non-linear expenditure system (Dumagan & Mount, 1991). Unlike the translog model (Christensen & Caves, 1980) and the "almost ideal demand system" or AIDS (Deaton & Muellbauer, 1980a and 1980b), this logit model is not derived from an explicit indirect utility function (translog) or from an expenditure function (AIDS). However, it has the same properties as the translog and AIDS with respect to additivity, global symmetry and zero–degree homogeneity. In addition, the logit model always predicts expenditure shares between zero and one, as should be the case, in contrast to the translog and AIDS models which could both predict negative shares. Moreover, the parameter constraints for the generalized logit model to have a negative semi-definite Hicks–Slutsky substitution matrix are less restrictive (Dumagan & Mount, 1991) than those required for the standard flexible functional forms, e. g., translog, AIDS, generalized Leontief and minflex Laurent models.

The properties of additivity, global symmetry and zero–degree homogeneity are embodied in the specification of the generalized logit model. While necessary, these are not sufficient for the computed Hicks–Slutsky substitution matrix to be negative semi–definite, either for a specific set of predicted expenditure shares or globally for all possible shares. By and large, negative semi–definiteness remains an empirical issue in this generalized logit model since there are no explicit restrictions to guarantee this result for all possible prices and income levels.

3.1 Non–Negativity and Additivity of Shares

Let the prices and corresponding quantities at any time period t be given by p_{it} and x_{it} , i = 1,2, . . . , n. Given that expenditures or income in the same period is I_t , then by definition of the budget constraint,

$$w_{it} = \frac{p_{it}\, x_{it}}{I_t} \quad ; \quad 1 \geq w_{it} \geq 0 \quad ; \quad \sum_{i=1}^{n} w_{it} = 1 \,. \qquad [3]$$

In [3], w_{it} is the expenditure share of each commodity. In order to satisfy [3], define a logit specification of these shares,

$$w_{it} = \frac{e^{f_{it}}}{e^{f_{1t}} + \ldots + e^{f_{nt}}} = \frac{e^{f_{it}}}{\sum_{j=1}^{n} e^{f_{jt}}} \quad [4]$$

where f_{it} is a function of p_{it}, $i = 1,2,\ldots,n$ and I_t. By defining the share w_{nt} of an arbitrarily chosen nth good in accordance with [4], it follows that

$$\ln\left(\frac{w_{it}}{w_{nt}}\right) = f_{it} - f_{nt} \quad ; \quad i = 1,2,\ldots,n-1 . \quad [5]$$

Thus, the non–linear expenditure system implied by [4] can be estimated as a linear system in [5] by specifying f_{it} as a linear function in [7] below.

The logit specification guarantees that the non–negativity and additivity of expenditure shares are satisfied no matter how f_{it} is specified.[2] This is because [4] strictly satisfies [3] for every set of predicted shares.

3.2 Zero–Degree Homogeneity in Prices and Income

By equating w_{it} in [3] to that in [4],

$$\ln x_{it} = -\ln\left(\frac{p_{it}}{I_t}\right) + f_{it} - \ln \sum_{j=1}^{n} e^{f_{jt}} \quad [6]$$

The demand functions x_{it} in [6] are homogeneous of degree zero in prices and income given the following specification,

$$f_{it} = \alpha_{io} + \sum_{j=1}^{n} \alpha_{ij}\, \theta_{ij(t-1)} \ln\left(\frac{p_{jt}}{p_{it}}\right) + \beta_i \ln\left(\frac{I_t}{p_{it}}\right) \quad [7]$$

where α_{io} and α_{ij} are parameters; and $\theta_{ij(t-1)}$ is a lagged variable weight which will be shown later to determine global Hicksian symmetry.

[2]In contrast, other models can predict nonsensical negative shares. For example, Lutton & LeBlanc (1984) showed that the translog can generate negative share predictions.

It follows from [6] and [7] that the own–price, cross–price and income elasticities in a generalized logit model are

$$E_{iit} = -1 - (1 - w_{it}) \left(\sum_{k=1}^{n} \alpha_{ik}\, \theta_{ik(t-1)} + \beta_i \right) - \sum_{k=1}^{n} w_{kt}\, \alpha_{ki}\, \theta_{ki(t-1)} \; ; \qquad [8]$$

$$E_{ikt} = \alpha_{ik}\, \theta_{ik(t-1)} - \sum_{i=1}^{n} w_{it}\, \alpha_{ik}\, \theta_{ik(t-1)} + w_{kt} \left(\sum_{i=1}^{n} \alpha_{ki}\, \theta_{ki(t-1)} + \beta_k \right) \; ; \qquad [9]$$

$$E_{iIt} = 1 + (1 - w_i)\, \beta_i - \sum_{k=1}^{n} w_{kt}\, \beta_k \quad ; \quad i \neq k \; . \qquad [10]$$

It can be verified from these elasticities that for any good,

$$\sum_{j=1}^{n} E_{ijt} + E_{iIt} = 0 \; . \qquad [11]$$

The result in [11] means that the logit specification satisfies Marshallian zero–degree homogeneity in prices and income.[3]

3.3 Symmetry of the Hicksian Cross–Price Effects

One disadvantage of direct specification of a demand system, as opposed to deriving it from an expenditure function or indirect utility function, is the need to check for symmetry (Lau, 1976).[4] However, Hicksian symmetry of the

[3]For this result, it is sufficient to define Marshallian demand for any good as a function of the ratios of its own price to income and to the prices of the other goods. For example, this condition is satisfied by the model specification in 6 and 7. This insures that proportional changes in all prices and income will leave demand unchanged, which is required by the above homogeneity property. This property implies the result in 11.

[4]If the hypothesized expenditure function is twice continuously diffferentiable with respect to prices, symmetry of the Hicksian cross–price effecsts follows by Shephard's lemma and Young's theorem. If the expenditure function is invertible, i. e., the indirect utility function is obtainable, Roy's identity yields the Marshallian demand system. From this, Hicksian symmetry can be verified by means of the Slutsky equation. Thus, symmetry is automatic for demand systems derived from expenditure functions with the above properties but not for demand systems directly specified. Hence, the need to check for symmetry in the latter case.

cross–price effects can be obtained in the logit model above by defining θ as the following function of lagged shares and by imposing symmetry on the α coefficients,

$$\theta_{ik(t-1)} = \frac{w_{k(t-1)}^{\gamma}}{w_{i(t-1)}^{1-\gamma}} \quad ; \quad w_{i(t-1)} = \frac{p_{i(t-1)}\ x_{i(t-1)}}{I_{(t-1)}} \quad ; \quad \alpha_{ik} = \alpha_{ki} \qquad [12]$$

where γ is a parameter[5]. To show that [12] is sufficient for global Hicksian symmetry, consider the Slutsky equation

$$\frac{\partial x_{it}}{\partial p_{kt}} = \frac{\partial x_{it}^{h}}{\partial p_{kt}} - x_{kt} \frac{\partial x_{it}}{\partial I_t} \qquad [13]$$

where x_{it}^{h} and x_{kt}^{h} are Hicksian demand functions whereas x_{it} and x_{kt} are Marshallian. Now, the Hicksian cross–price effect in [13] can be expressed in terms of Marshallian price and income elasticities and budget shares as

$$\frac{\partial x_{it}^{h}}{\partial p_{kt}} = \frac{I_t}{p_{it}\ p_{kt}} (E_{ikt}\ w_{it} + w_{it}\ w_{kt}\ E_{iIt}) \qquad \text{or} \qquad [14]$$

$$\frac{\partial x_{kt}^{h}}{\partial p_{it}} = \frac{I_t}{p_{kt}\ p_{it}} (E_{kit}\ w_{kt} + w_{kt}\ w_{it}\ E_{kIt}) \ . \qquad [15]$$

Symmetry of the Hicksian cross–price effects holds in the generalized logit model for any set of predicted budget shares. For infinitesimal changes of shares, the time lag defined by the original data, t–1 , may be replaced by an infinitesimal lag, $t-\delta$ where $\delta \to 0$. This means that the elasticities may be computed conditionally, using on the right-hand side the shares evaluated at time t , i.e., using the current value in place of the lagged value of θ in [12]. In

[5]Considine's (1990) model is a special case of the generalized logit model in the sense that his global symmetry restriction may be obtained from 12 by setting $\gamma = 1$, thus eliminating the denominator of θ, and then replacing the actual lagged value of the share w_k by its predicted value. His symmetry restrictions on the price parameters are equivalent to the above restrictions on the α coeficients.

this case, omitting the time subscript t for simplicity, it can be verified that

$$w_i\, \theta_{ik} = w_k\, \theta_{ki}\,. \qquad [16]$$

In view of [16], the price elasticities in [8] and [9] simplify to

$$E_{ii} = -1 - \sum_{k=1}^{n} \alpha_{ik}\, \theta_{ik} - (1 - w_i)\, \beta_i \;; \qquad [17]$$

$$E_{ik} = \alpha_{ik}\, \theta_{ik} + w_k\, \beta_k\,. \qquad [18]$$

The income elasticities remain the same as in [10], which are,

$$E_{iI} = 1 + (1 - w_i)\, \beta_i - \sum_{k=1}^{n} w_k\, \beta_k\,. \qquad [19]$$

Substituting these elasticities into [14] and [15] gives the Hicksian own-price and cross-price effects,

$$\frac{\partial x_i^h}{\partial p_i} = -\frac{I}{p_i^2}\left[w_i - w_i^2 + \sum_{k=1}^{n} \alpha_{ik}\, (w_i\, w_k)^\gamma + (w_i - 2\, w_i^2)\, \beta_i + w_i^2 \sum_{j=1}^{n} w_j\, \beta_j \right]; \qquad [20]$$

$$\frac{\partial x_i^h}{\partial p_k} = \frac{I}{p_i\, p_k}\left[w_i\, w_k + \alpha_{ik}\, (w_i\, w_k)^\gamma + w_i\, w_k\, (\beta_i + \beta_k) - w_i\, w_k \sum_{j=1}^{n} w_j\, \beta_j \right]; \qquad [21]$$

$$\frac{\partial x_k^h}{\partial p_i} = \frac{I}{p_k\, p_i}\left[w_k\, w_i + \alpha_{ki}\, (w_k\, w_i)^\gamma + w_k\, w_i\, (\beta_k + \beta_i) - w_k\, w_i \sum_{j=1}^{n} w_j\, \beta_j \right]. \qquad [22]$$

The Hicksian cross-price effects in [21] and [22] are symmetric given the parameter restriction that $\alpha_{ik} = \alpha_{ki}$ in [12]. Global symmetry holds for every set of shares and for any value of γ.

The global symmetry result above is conditional on the equality between the "approximate" short-run elasticities in [17] to [19] and the "true" short-run elasticities in [8] to [10]. These elasticities are equal given the assumption of fixed expenditure shares in [12], which is reasonable in the short–run. Hence, the global symmetry between [21] and [22] implies that there exists in principle an underlying expenditure function or indirect utility function that could generate the logit model (Samuelson, 1950; Katzner, 1970; Hurwicz & Uzawa, 1971; Johnson, Hassan & Green, 1984; Varian, 1984; LaFrance & Haneman, 1989).[6]

4. Residential Energy Demand in New York State (1960–1987)

A dynamic and stochastic version of the generalized logit model of expenditure shares was fitted to residential sector data for the state of New York from 1960 to 1987 on the consumption of electricity, natural gas and fuel oil, including a composite "other" good category to complete the demand system. For this purpose, [7] is respecified (Dumagan, 1991) as

$$f_{it} = \alpha_{io} + \sum_{j=1}^{n} \alpha_{ij}\, \theta_{ij(t-1)} \ln\left(\frac{p_{jt}}{p_{it}}\right) + \beta_i \ln\left(\frac{I_t}{p_{it}}\right) + \lambda_i \ln x_{i(t-1)} + e_{it} \qquad [23]$$

where $x_{i(t-1)}$ is lagged quantity of good i and e_{it} is a stochastic error term. This respecification does not change the short–run elasticities in [17], [18] and [19] but introduces a different set of long–run elasticities.

Table 1 presents the estimates of the price, income and lag parameters. The price parameters are symmetric, i. e. $\alpha_{12} = \alpha_{21}$, $\alpha_{13} = \alpha_{31}$, $\alpha_{14} = \alpha_{41}$, $\alpha_{23} = \alpha_{32}$

[6]By Shephard's lemma, the Hicksian demand functions are the first partial derivatives of the expenditure function with respect to prices. Thus, these demand functions form a system of partial differential equations. This system is integrable or has a solution, i. e., the expenditure function exists, if and only if the first order cross–partial derivatives of the system are symmetric. This integrability condition is equivalent to the symmetry of the second–order partial derivatives with respect to prices of the expenditure function, which is true by Young's theorem. Thus, the absence of symmetry not only violates Young's theorem but also implies that the Hicksian demand system is not integrable or that the expenditure function and its dual indirect utility function do not exist.

and $\alpha_{24} = \alpha_{42}$. Moreover, note from [23] that α_{ij} is not estimated when i = j since in this case the logarithm of the price ratio equals zero. The income parameters are β_1, β_2, β_3, and β_4. The lag coefficients are λ_1, λ_2, λ_3 and λ_4.

TABLE 1 — ESTIMATES OF PRICE, INCOME AND LAG PARAMETERS

PARAMETER	ESTIMATE	STD ERROR	T–RATIO
$\alpha_{12} = \alpha_{21}$	0.02466	0.00688	3.58
$\alpha_{13} = \alpha_{31}$	0.01134	0.00399	2.84
$\alpha_{14} = \alpha_{41}$	– 0.00351	0.00078	– 4.47
$\alpha_{23} = \alpha_{32}$	0.06215	0.00854	7.28
$\alpha_{24} = \alpha_{42}$	0.00229	0.00146	1.57
β_1	– 0.94216	0.00552	– 170.55
β_2	– 0.89085	0.00978	– 91.02
β_3	– 0.80782	0.01421	– 56.84
β_4	– 0.65919	0.04107	– 16.05
λ_1	0.81398	0.02024	40.21
λ_2	0.76135	0.02104	36.18
λ_3	0.50438	0.02815	17.92
λ_4	0.67261	0.04244	15.85

Source: Dumagan (1991).

The t–ratios of the estimated parameters are relatively large (absolutely greater than 2) with only one exception, α_{24} . Moreover, the estimated model fits the data very well with R–square values close to one for each equation.[7]

[7]Dumagan (1991) gives all the pertinent goodness of fit statistics.

4.1 Consistency of the Estimates With Consumer Theory

In Table 2, the matrix denoted by SRPIE gives the short–run price and income elasticities of demand computed at the point of means. The rows define the quantities (QTY), namely, EL for electricity, NG for natural gas, OL for oil and OT for the other composite good. The second to the fifth columns are for the prices and the sixth is for income. Thus, the diagonal elements of the first four rows and the four columns are the own–price elasticities and the off–diagonal elements are the cross–price elasticities. Notice that all the own–price elasticities are negative as implied by normality of the goods, which is consistent with the fact that all the income elasticities in the sixth column are positive. The cross–price elasticities are positive among the energy goods, implying substitution between electricity, natural gas and oil. However, the cross–price elasticities with the other composite good are negative, implying complementarity. Finally, it can be verified that the sum of the elasticities in a given row is zero because of zero–degree homogeneity in prices and income of the underlying Marshallian demand function.

TABLE 2 — SHORT–RUN PRICE AND INCOME ELASTICITIES AT THE POINT OF MEANS

SRPIE	EL PRICE	NG PRICE	OL PRICE	OT PRICE	INCOME
EL QTY	– 0.0666	0.0153	0.0036	– 0.6755	0.7232
NG QTY	0.0165	– 0.2266	0.0529	– 0.6175	0.7745
OL QTY	0.0030	0.0566	– 0.6559	– 0.2612	0.8576
OT QTY	– 0.0098	– 0.0079	– 0.0035	– 0.9850	1.0062

Source: See Table 1.

The matrix denoted by HSSM in Table 3 is the Hicks–Slutsky substitution matrix also computed at the point of means. The diagonal elements are all negative and the off–diagonal elements are symmetric as required by theory. It can be shown that the sum of the elements in the same row weighted by the prices is zero because of zero–degree homogeneity in prices of the underlying Hicksian demand function.

TABLE 3 — HICKS–SLUTSKY SUBSTITUTION MATRIX (HSSM) AT THE POINT OF MEANS

HSSM	EL PRICE	NG PRICE	OL PRICE	OT PRICE
EL QTY	– 0.0189	0.0270	0.0097	0.1645
NG QTY	0.0270	– 0.9449	0.2090	2.8037
OL QTY	0.0097	0.2090	– 1.7217	8.9139
OT QTY	0.1645	2.8037	8.9139	– 68.7688

Source: See Table 1.

Finally, EVA in Table 4 gives the eigenvalues of the HSSM in Table 3. All are non–positive and one of them is zero. Thus, the HSSM is negative semi–definite, implying that the estimated model is consistent with the theory of utility maximization at the mean values of the expenditure shares.

TABLE 4 — EIGENVALUES OF THE HSSM AT THE POINT OF MEANS

EVA	COL 1
ROW 1	– 3.7E–15
ROW 2	– 0.1277
ROW 3	– 1.2829
ROW 4	– 70.0437

Source: See Table 1.

It can be verified that the symmetry and negative semi–definiteness of the HSSM holds at every data point of the sample of observations. Thus, it is not surprising that this result holds at the point of means. This finding is significant in that it implies that the estimated model embodies utility–maximizing behavior. Therefore, this model is valid as a basis for measuring the welfare effects of price and income changes in combination with the money metric welfare measure. In principle, this measurement of welfare effects can start from any data point in the sample. This is warranted by the finding that the HSSM is symmetric and negative semi–definite at every sample observation.

5. Energy Demand Elasticities of Typical Households Calibrated From the Statewide Residential Model

For the purposes of this paper, hypothetical households with specified energy consumption characteristics are defined to represent low ($15,000), middle ($30,000) and high ($60,000) annual income levels (see Table 5). Combining the fuel prices and the consumption levels in this table yield expenditure shares for each fuel type as well as the expenditure share of the residual "other" good category for each household type. These expenditures shares, consumption and income levels are then combined with the parameter estimates from the statewide residential energy demand model in Table 1 to arrive at the short-run price and income elasticities of demand shown in Tables 6, 7 and 8 for each of the nine types of households, differentiated by income and by the type of heating fuel used.

The flexibility of the generalized logit model is illustrated by using the parameter estimates from the statewide residential energy demand system to calibrate energy demand elasticities for different households. These show that the generalized logit model can distinguish between the demand elasticities for the same good of households that consume different other goods, e. g., the demand elasticities for electricity between households that use either electricity, natural gas or oil for heating. These tables display a theoretical attribute of the generalized logit elasticities that has important implications for empirical work.

It is in the nature of econometric estimates using aggregate data that the estimated parameters apply not only to the aggregate economic unit as a whole but also to the groups or subgroups subsumed under the aggregate. However, it is not simply interesting but quite important in applied demand analysis to be able to distinguish between group differences in demand for the same commodity. An interesting example is the difference in demand elasticities for electricity between households that use either electricity, natural gas or fuel oil for space heating. This can easily be handled by the elasticity formulas in the generalized logit model given by [17] to [19]. For instance, since by definition an all–electric household does not buy natural gas or fuel oil, then the own–price, cross–price and income elasticities for electricity of this household can be computed simply by setting to zero the expenditure share of natural gas, fuel oil and the share of any good included in the demand system which the household does not buy.

In general, differences in demand elasticities for the same good between diverse groups can be determined from the fact that in the generalized logit model the elasticity of demand by an individual (or by any grouping of individuals) for any good i that it buys is unaffected by the change in the price of any other good that it does not buy. This result comes out naturally from the generalized logit but is not exhibited by the other demand models such as the AIDS and translog.

TABLE 5 -- SPECIFIED CHARACTERISTICS OF HOUSEHOLDS AT DIFFERENT INCOME LEVELS

($15,000 Annual Income)		
Fuel Used For Heating	Space and Water Heating (MMBtu)	Other Uses For Electricity (MMBtu)
Electricity	80	30
Natural Gas	120	30
Oil	120	30

($30,000 Annual Income)		
Fuel Used For Heating	Space and Water Heating (MMBtu)	Other Uses For Electricity (MMBtu)
Electricity	100	50
Natural Gas	150	50
Oil	150	50

($60,000 Annual Income)		
Fuel Used For Heating	Space and Water Heating (MMBtu)	Other Uses For Electricity (MMBtu)
Electricity	140	80
Natural Gas	210	80
Oil	210	80

Source: See Table 1.

TABLE 6 -- SHORT-RUN PRICE AND INCOME ELASTICITIES OF DEMAND FOR HOUSEHOLDS BY THE TYPE OF FUEL USED FOR HEATING (LOW INCOME HOUSEHOLDS)

Electricity Heated Home
($15,000 Annual Household Income)

	EL	NG	OIL	OTHER	INCOME
EL	– 0.2202	0	0	– 0.5478	0.7680
NG	0	0	0	0	0
OIL	0	0	0	0	0
OTHER	– 0.1715	0	0	– 0.8795	1.0510

Natural Gas Heated Home
($15,000 Annual Household Income)

	EL	NG	OIL	OTHER	INCOME
EL	– 0.1147	– 0.0213	0	– 0.6071	0.7431
NG	– 0.0225	– 0.1893	0	– 0.5826	0.7944
OIL	0	0	0	0	0
OTHER	– 0.0471	– 0.0463	0	– 0.9327	1.0261

Oil Heated Home
($15,000 Annual Household Income)

	EL	NG	OIL	OTHER	INCOME
EL	– 0.1007	0	– 0.0297	– 0.6081	0.7385
NG	0	0	0	0	0
OIL	– 0.0352	0	– 0.3924	– 0.4453	0.8729
OTHER	– 0.0471	0	– 0.0329	– 0.9415	1.0215

Source: See Table 1.

TABLE 7 -- SHORT-RUN PRICE AND INCOME ELASTICITIES OF DEMAND FOR HOUSEHOLDS BY THE TYPE OF FUEL USED FOR HEATING (MIDDLE INCOME HOUSEHOLDS)

Electricity Heated Home
($30,000 Annual Household Income)

	EL	NG	OIL	OTHER	INCOME
EL	– 0.1639	0	0	– 0.5878	0.7517
NG	0	0	0	0	0
OIL	0	0	0	0	0
OTHER	– 0.1167	0	0	– 0.9179	1.0347

Natural Gas Heated Home
($30,000 Annual Household Income)

	EL	NG	OIL	OTHER	INCOME
EL	– 0.1017	– 0.0071	0	– 0.6274	0.7362
NG	– 0.0109	– 0.1780	0	– 0.5985	0.7875
OIL	0	0	0	0	0
OTHER	– 0.0392	– 0.0288	0	– 0.9512	1.0191

Oil Heated Home
($30,000 Annual Household Income)

	EL	NG	OIL	OTHER	INCOME
EL	– 0.0896	0	– 0.0157	– 0.6280	0.7333
NG	0	0	0	0	0
OIL	– 0.0256	0	– 0.4208	– 0.4212	0.8677
OTHER	– 0.0392	0	– 0.0192	– 0.9579	1.0163

Source: See Table 1.

TABLE 8 -- SHORT-RUN PRICE AND INCOME ELASTICITIES OF DEMAND FOR HOUSEHOLDS BY THE TYPE OF FUEL USED FOR HEATING (HIGH INCOME HOUSEHOLDS)

Electricity Heated Home
($60,000 Annual Household Income)

	EL	NG	OIL	OTHER	INCOME
EL	– 0.1312	0	0	– 0.6112	0.7424
NG	0	0	0	0	0
OIL	0	0	0	0	0
OTHER	– 0.0856	0	0	– 0.9398	1.0254

Natural Gas Heated Home
($60,000 Annual Household Income)

	EL	NG	OIL	OTHER	INCOME
EL	– 0.0903	0.0003	0	– 0.6415	0.7316
NG	– 0.0013	– 0.1737	0	– 0.6079	0.7829
OIL	0	0	0	0	0
OTHER	– 0.0314	– 0.0200	0	– 0.9631	1.0145

Oil Heated Home
($60,000 Annual Household Income)

	EL	NG	OIL	OTHER	INCOME
EL	– 0.0790	0	– 0.0086	– 0.6419	0.7296
NG	0	0	0	0	0
OIL	– 0.0170	0	– 0.4534	– 0.3935	0.8639
OTHER	– 0.0314	0	– 0.0126	– 0.9686	1.0125

Source: See Table 1.

Notice from the elasticity tables that the own–price elasticities are negative and the income elasticities are all positive, which are consistent with earlier findings in the statewide case that all the goods are normal. But in contrast, all the cross–price elasticities are negative implying complementarity. A possible explanation is that with one less good in each case compared to the statewide results, there are less substitution possibilities thus tending towards more complementarities. Notice, however, that the price elasticities increase algebraically with income, i. e., become less negative. For example, the cross–price elasticity of demand for electricity of a natural gas heated home became slightly positive (0.0003) at $60,000 income. This implies a move towards substitutability which is made possible by rising incomes. Also, the goods are becoming more own–price inelastic with higher incomes. Perhaps, it is because with rising incomes, the expenditure shares on the goods are becoming smaller. Hence, a price increase can easily be accommodated without too much sacrifice in consumption. These show that the economic logic of the model can still be reflected in the behavior of households that may lie in the fringes of the sample used in model estimation.

For all the nine households in Tables 6, 7 and 8, zero–degree homogeneity in prices and income is satisfied from the fact that the sum of price and income elasticities for each good equals zero. Also, the non–negativity and additivity of expenditures shares to one are guaranteed by the specification of the generalized logit model. More importantly, for each of these nine households, the Hicks–Slutsky substitution matrix can be verified to be symmetric and negative semi–definite, implying that these households are consistent with utility–maximizing behavior. It follows that the demand elasticities and expenditure shares in each of the nine household categories may be used in the money metric measure to determine the welfare effects on the households of policies that change incomes and/or the prices that these households pay for any or all of the four goods.

6. Household Welfare Effects of Carbon Penalties on Electricity and Fuels

It is plausible to argue that the costs of environmental externalities from energy production may be internalized by incorporating them in consumer prices by means of taxation of these externalities. The argument rests on the fact that energy is generated to satisfy consumer demand and providing energy at least cost to consumers entails using inputs that dirty the environment, e. g., burning coal that emits carbon in generating electricity. In this example, a carbon tax may be passed on to consumers by raising the price of electricity generated by burning coal. By similar argument, a carbon tax should be reflected by raising the prices of other carbon-emitting fuels.

For the purposes of this analysis, the emission rates of carbon in pounds per million Btu (Lbs./MMBtu) are shown in the second column of Table 9. Two separate cases are analyzed: (1) an emissions penalty on electricity only of $ 0.014 per Kwh and (2) a tax on electricity and fuels of $ 100 per ton (2,000 lbs.) of carbon. This penalty/tax can be converted into an equivalent penalty/tax per MMBtu which is then added to the prices in the second column of the table. These data, in combination with all the other information in the preceding four tables, are used as inputs into the money metric model in section 2 to yield the welfare effects shown in Table 10.

TABLE 9 -- PRICES AND EMISSION RATES FOR FUELS AND ELECTRICITY

Fuel Used For Heating	Price ($/MMBtu)	Carbon Emissions (Lbs./MMBtu)
Electricity	30.99	85.19
Natural Gas	6.53	31.84
Oil	6.35	40.44

Source: Mount & Czerwinski (1989).

In the framework of the money metric, the welfare effects of the emissions penalty on electricity only are analytically different from those of the carbon tax on electricity and fuels. The emissions penalty involves an increase in the price of electricity only, whereas the carbon tax raises all the electric and fuel prices. Thus, the welfare effects of the electric emissions penalty take into consideration only the demand elasticities for electricity. However, the welfare effects of the carbon tax must consider all the demand elasticities for electricity and fuels.

A pattern of results is evident from Table 10 that uniformly applies to the welfare effects of both the electric emissions penalty and the carbon tax. It is the fact that the absolute values of the welfare losses rise with income but fall as a proportion of income in either case.

Notice that the welfare effects of the emissions penalty on all--electric households are almost the same as the welfare effects on all--electric households of the carbon tax. The reason for this is that the emissions penalty and the carbon tax on electricity result in almost equal percentage

TABLE 10 – WELFARE EFFECTS OF CARBON PENALTIES BY TYPE OF HOUSEHOLD (DOLLARS/HOUSEHOLD/YEAR & AS A PERCENT OF HOUSEHOLD INCOME/YEAR)

An Emissions Penalty on Electricity Only ($0.014/Kwh)

Fuel Used for Heating	Annual Income $15,000	$30,000	$60,000
Electricity	– $ 438.54	– $ 602.94	– $ 888.45
	– 2.92 %	– 2.01 %	– 1.48 %
Natural Gas	– $ 121.61	– $ 203.01	– $ 325.27
	– 0.81 %	– 0.68 %	– 0.54 %
Oil	– $ 121.75	– $ 203.20	– $ 325.56
	– 0.81 %	– 0.68 %	– 0.54 %

A Tax on Carbon Emissions Applied to Electricity, Natural Gas and Oil ($100/Ton of Carbon)

Fuel Used for Heating	Annual Income $15,000	$30,000	$60,000
Electricity	– $ 454.78	– $ 625.45	– $ 921.77
	– 3.03 %	– 2.08 %	– 1.54 %
Natural Gas	– $ 310.48	– $ 442.43	– $ 663.35
	– 2.07 %	– 1.47 %	– 1.11 %
Oil	– $ 351.87	– $ 493.14	– $ 732.75
	– 2.35 %	– 1.64 %	– 1.22 %

Source: See Table 1.

changes in the price of electricity. In this example, the emissions penalty raises electricity price by 13.24 % and the carbon tax raises it by 13.74 %. However, the welfare loss is considerably lower as a percentage of income. For the all–electric home, the emissions penalty and the carbon tax both decrease welfare by about – 3 % when income is $ 15,000, by around – 2 % at an income of $ 30,000, and in the order of – 1.5 % at $ 60,000 income.

Also, given the same income, the welfare losses from the emissions penalty are considerably lower for households that use natural gas or oil for water and space heating. The welfare losses from the emissions penalty range in the neighborhood of – 0.8 % to – 0.5 % compared to the losses from the carbon tax from around – 2 % to about – 1 % of income. This reflects the fact that the electric costs of non–heating uses are a relatively small proportion of total energy costs, and that the prices of natural gas and oil do not rise since the penalty is on electricity only.

Finally, it may be observed that the welfare losses from the emissions penalty (on electricity only) appear to be equal for households that use natural gas or oil for heating. The reason for this is twofold. First, it is assumed in Table 5 that the electricity consumption levels for non–heating uses are equal for all households with the same annual incomes. Second, as shown in Tables 6, 7, and 8, the price and income elasticities of demand for electricity are almost equal between households with the same annual incomes that use either natural gas or oil for heating. These two conditions logically imply that the welfare losses would almost be equal.

7. Conclusion

The calibration of the demand elasticities of the hypothetical households in this paper, using the estimated parameters of the generalized logit model, demonstrated a theoretical attribute of the generalized logit elasticities that has important implications for empirical work. It is in the nature of econometric applications using aggregate data that the estimated parameters are applied not only to the average economic unit as a whole but also to the other units that are of interest. However, it is important that the economic logic of the estimated model does not breakdown when different units are used. An interesting example is the difference in demand elasticities for electricity between households that use either electricity, natural gas or fuel oil for space heating. This can easily be handled by the elasticity formulas in the generalized logit model. For instance, since by definition an all–electric household does not buy natural gas or fuel oil, then the cross–price elasticities for natural gas and oil of this household are zero as they should be. This is typically not the case with the other demand systems.

In general, this paper showed that the theoretically consistent properties of the generalized logit model are exemplified even by hypothetical households with economic attributes that may place them in the fringes of the actual sample of observations used to estimate the model. Examples are the nine hypothetical households that are differentiated by three levels of income and three sources of heating. For these households, the additivity, homogeneity and symmetry results are not surprising since these are analytically embedded in the model. The major empirical finding in this regard is that the Hicks–Slutsky substitution matrix, which is guaranteed to be symmetric, is also negative semi–definite. This is necessary to validate the empirical model as a basis of welfare change analysis since this result implies that the model embodies utility–maximizing or expenditure–minimizing behavior.

Therefore, the application in this paper of the money metric, using the estimated parameters of the generalized logit model, to the evaluations of the welfare effects of emissions penalties or carbon taxes are, in principle, valid. The importance of the results from this application is not so much in the numerical values but in demonstrating that (1) the generalized logit model can be calibrated to represent different types of households without violating the desirable economic properties of the model; (2) the demand elasticities for different households change in a logically consistent way (e. g., demand is less price elastic if the expenditure for the commodity is only a small proportion of income); and (3) the money metric measure of welfare change can be used to evaluate a wide variety of environmental policies.

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